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RISØ'S DESIGN BASIS FOR SMALL TO MEDIUM SIZE DANISH WINDMILLS

Per Lundsager and Peter Hjuler Jensen
The Test Station for Windmills

Abstract. The report presents a simple design basis for Danish windmills. The design basis has beeen developed in connection with the licensing of windmills at the Test Sation. The background for the developemnt of the design basis is outlined, and the design load cases are defined. The load cases are applicable in the condition that a number of functional requirements are fulfillled, and these requirements are specified. Finally, the impact of the design basis on the development of windmill failure rates and performances is outlined.

EDB-descriptors: DENMARK; DESIGN; DYNAMIC LOADS; HORIZONTAL AXIS TURBINES; LICENSING; PERFORMANCE

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1. INTRODUCTION

The development of small to medium size windmills in Denmark, i.e. windmills up to approx. 300 kW rated power, has been a remarkable industrial success. During the decade since the energy crisis in 1973 this development has reached a level where a well-established Danish windmill industry now produces windmills for export totalling approx. 100 million US dollars (1984).

A combination of efforts are responsible for this success: a rather strong and reasonably consistent governmental support of the development and application of windmills, the formation of manufacturers and consumers unions, the de facto acceptance of windmills by electric utilities and local communities together with the introduction of a public licensing procedure as early as 1979. This has resulted in the creation of an environment in Denmark that has been well suited for the introduction of this new energy technology.

The so-called Danish windmill concept, i.e. the three-bladed, fixed-pitch upwind rotor dual-induction generator windmill, has achieved worldwide recognition for dependability and ruggedness. One major reason for this has been the development at the Test Station for Windmills of a relatively simple but working design basis in connection with a licensing procedure that contains a number of functional requirements.

This paper gives the background for the development of this design basis and presents its main features. The functional requirements of the licensing procedure are also described and the future developments of windmill standards in Denmark are outlined.

2. HISTORICAL BACKGROUND

The development of windmills in Denmark has been described at a number of occasions (see, for example, Lundsager (1982) and Jensen (1984)). The "grandfather" of the Danish windmill concept is the Gedser Windmill of 200 kW, built in 1958, whose principal features are still to be found in current Danish designs.

The design was successful in the sense that its principal philosophy was proven adequate as the windmill did not suffer any major breakdowns during its 10 years of operational life. The outline of safety and design philosophy (Juul, 1961) may therefore be considered the foundation of the design basis presently in use for the Danish concept.

No development of windmill design basis was done between the release of this work and the energy crisis in 1973. Development of windmills in Denmark during the years from 1973 until the introduction of the concept of licensing in 1979 was therefore very much based on trial-and-error, and a considerable number of painful experiences were suffered by windmill pioneers.

Fig. 1. Total failure following run-away due to lack of aerodynamic brakes (1979).

Experiences such as the one shown in Fig. 1 led the Test Station for Windmills that has administered the licensing procedure since its introduction to adopt two main design features of the Gedser Windmill. One was the requirement that the blades, rotor and tower be able to withstand a static thrust of 300 N per square meter swept rotor area. The other was the requirement that the blades be equipped with aerodynamic brakes, operating automatically and independently of the mechanical brake.

The static thrust requirement was soon extended to a requirement that each blade type should be tested to withstand a triangular distributed proof load corresponding to 300 N/m2, Pedersen (1981). This was a consequence of events such as the one shown in Fig. 2.

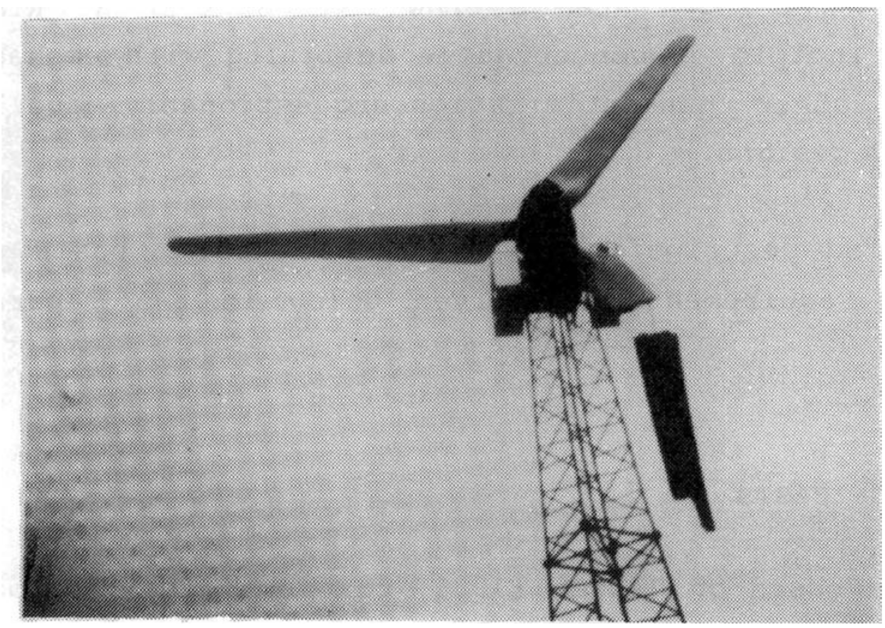

Fig- 2. Failure of GRP standard blade caused by the use of yaw error to limit power output (1981).

The problem of operating a licensing procedure in the early years was how to prescribe design loads, stress and stiffness limits, etc. for a vigorous industry developing a new technology in the absence of any established design basis. The solution was to establish an ad-hoc design basis in combination with specified functional requirements. The design basis is developed on the basis of practical experience in collaboration with the manufacturers and on the basis of measurements and theoretical work at the Test Station, such as that by Rasmussen (1982, 1983). Also work done in relation to the Nibe wind turbines has been used (Lundsager et al., 1981).

One way of solving the design basis problem, was to "design around the problem". An example is the licensing requirement that the yawing out of the wind must not be used to limit power output. This was a consequence of the work by Rasmussen (1982) showing that excessive oscillating loads would result from such a procedure. Another example, although not a requirement, has been the application of 3-bladed rotors, whereby the more complicated dynamics of 2-bladed rotors was avoided. This way of solving "around the problem" seems to be unique for Denmark, but it has worked remarkably well as indicated by Fig. 3 showing the windmills being tested at the Test Station at Risø. However, the principle of conservative designing with emphasis on reliability rather than optimization unquestionably have led to rather heavy designs.

The more detailed description of the ad-hoc design basis and the functional requirements are given below in two separate sections.

3. RISØ'S DESIGN BASIS

This chapter is based on Jensen (1985) that outlines the loads to be applied in the design of Danish windmills to be licensed. As is customary in Danish standards the load requirements are not indispensable. If the designer may prove by analysis or other means that his design need not withstand certain specified loads, the design may be licensed for a different set of loads.

This possibility is included in the application of the design basis for several reasons. The two most important are: (1) the design basis is developed from years of experience with the

Fig. 3. Windmills being tested at Ris0 (1984).

so-called Danish concept and therefore allowance must be made for different design approaches, and (2) at this stage in the development a too rigorous enforcement of a design basis that is semiempirical may prevent the development of an improved design.

3.1. Design loads

The existing practice for licensing in Denmark is to a large extent based on the simple load cases given below, combined with the experience collected at the Test Station. The loads are conservative values that may be changed if the necessary documentation is available.

The loads are developed for horizontal-axis, stall-regulated, grid-connected windmills with active yaw, operating at approximately constant rpm. The rotor diameter is between 5 and 25 m, the tip speed in the range 35 to 50 m/s and rpm in the range 35 to 120 rpm. The solidity is approx. 10%.

This description fits the majority of windmills commercially available in Denmark.

Figure 4 shows the rotor coordinates in which the loads are prescribed. The loads are caused mainly by aerodynamic forces, gravity forces and acceleration forces on the rotor.

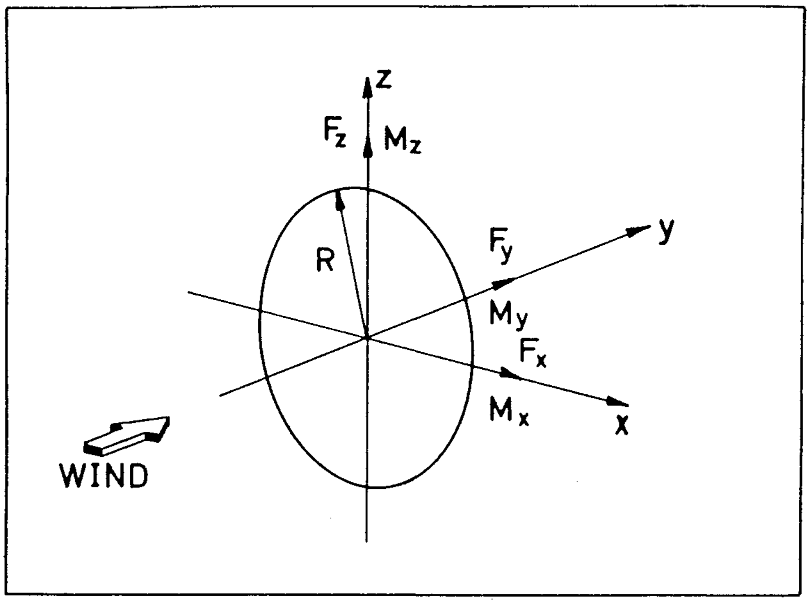

Fig. 4. Coordinate system used for the definition of rotor loads.

The x-axis is horizontal and perpendicular to the y-axis which coincides with the main shaft axis. The z-axis although perpendicular to these two axes need not be parallel to the tower axis.

In the following sections the forces in the three directions are given. The forces given explicitly below are those on the rotor acting at its center. The forces are given in the form

$$F = F_{nom} \pm dF \qquad (1)$$

where F is the generalized force to be used in the design
F_{nom} is the static component corresponding to the conditions at nominal power.
dF is the oscillating component.

The dynamic component dF is defined for two applications: One is denoted dF_1 and is intended for use on the rotor blades. The other is denoted dF_2 for use on the machinery and the tower. Generally, dF_1 is larger in amplitude than dF_2 due to: (1) the averaging effect of the rotor on shaft loads and (2) the assumption that the dynamic amplification factor for these forces is less than unity.

This latter assumption reflects the fact that the loads are valid only when the following conditions are met:

- Natural frequencies must be separated from the excitation frequencies, notably 1P, 2P and 3P, by at least 10%, depending on the damping.

- The dynamic loads are defined for loadings that occur more than 10^7 times during a lifetime.

When using stresses based on these loads, safety factors on material properties and production accuracy must be used. All forces and torques are given in N or Nm, respectively.

3.1.1. Forces in the x-direction.

F_x is the total sideforce on the rotor. In this context it is given as

$$F_x = 0, \tag{2}$$

i.e. no static or dynamic sideforce is prescribed directly. The loads on the yaw mechanism are defined in section 3.1.3.

M_x is the total moment around the x-axis. It is given by

$$M_x = M_{x,nom} \pm dM_x \tag{3}$$

The static component is assumed to be caused by an offset from the center of the static horizontal force $F_{y,nom}$, cf. section 3.1.2. That is:

$$M_{x,nom} = 0.167 \cdot R \cdot F_{y,nom}, \tag{4}$$

where R is the radius of the rotor.

The dynamic moment on the rotor is given as:

$$dM_{x1} = 0.042 \cdot R \cdot F_{y,nom} \tag{5}$$

corresponding to an offset of 0.167 R of the dynamic component dF_{y1} of section 3.1.2.

The dynamic moment to be applied to the machinery and tower top is given as:

$$dM_{x2} = 0.028 \cdot R \cdot F_{y,nom}, \tag{6}$$

corresponding to a 33% reduction of dM_{x1}.

3.1.2. Forces in the y-direction.

F_y is the total thrust on the rotor. It is given by

$$F_y = F_{y,nom} \pm dF_y. \tag{7}$$

The static component is given by:

$$F_{y,nom} = 300 \cdot A, \tag{8}$$

where A is the swept rotor area and 300 is the prescribed load intensity in N/m^2 swept rotor area.

$F_{y,nom}$ is the load used in proof load tests of windmill blades (Pedersen, 1981).

The dynamic force component on the rotor is given by:

$$dF_{y1} = 0.25 \cdot F_{y,nom}. \tag{9}$$

The dynamic force on the individual blade is dF_{y1} divided by the number of rotor blades.

The dynamic force on the machinery and the tower top is:

$$dF_{y2} = 0.15 \cdot F_{y,nom} \tag{10}$$

corresponding roughly to a 33% reduction of dF_{y1}.

M_y is the rotor torque and is given by:

$$M_y = M_{y,nom} \pm dM_y. \tag{11}$$

The static component $M_{y,nom}$ is related to $M_{e,nom}$, the torque at nominal rpm corresponding to rated electrical output, by

$$M_{y,nom} = 1.3\ M_{e,nom}. \tag{12}$$

The factor 1.3 corresponds to a conservative estimated efficiency of 0.77 of the power train.

The dynamic torque component dM_{y1} on the main shaft is given as:

$$dMy_1 = 0.25 \cdot M_{y,nom} \tag{13}$$

The dynamic torque component dM_{y2} transferred to the tower top is:

$$dM_{y2} = 0.15 \cdot M_{y,nom}, \tag{14}$$

corresponding roughly to a 33% reduction of dM_{y1}.

An additional main shaft torque is the brake torque from the mechanical torque. The brake torque M_{yb} is given by:

$$M_{yb} = 2.5\ M_{y,nom} \tag{15}$$

An additional force on each blade is caused by gravity, leading to an extra dynamic contribution to blade loading.

3.1.3. Forces in the z-direction.

F_z is the total vertical force given by:

$$F_z = F_{z,nom} \pm dF_z. \tag{16}$$

The static component $F_{z,nom}$ is caused by the mass of the rotor and is given by:

$$F_{z,nom} = - m \cdot g, \tag{17}$$

where m is mass of rotor and g the acceleration of gravity.

The dynamic component dF_z is equal to zero.

M_z is the total torque around the z-axis, defining the torque on components such as the yaw drive. M_z is given by

$$M_z = M_{z,nom} \pm dM_z \tag{18}$$

The static component $M_{z,nom}$ is assumed to be caused by an offset from the center of the static horizontal force $F_{y,nom}$ (see section 3.1.2). From this we infer

$$M_{z,nom} = 0.167 \cdot R \cdot F_{y,nom}, \tag{19}$$

where R is the radius of the rotor.

The dynamic moment on the rotor is given by:

$$dM_{z1} = 0.042 \cdot R \cdot F_{y,nom}, \tag{20}$$

corresponding to an offset of 0.167 R of the dynamic component dF_{y1} (see section 2.1.2).

The dynamic moment to be applied to the machinery and the tower top is given by:

$$dM_{z2} = 0.028 \cdot R \cdot F_{y,nom}, \tag{21}$$

corresponding to a 33% reduction of dM_{z1}.

3.1.4. Summary of Design Loads.

The design loads are based on the static thrust $F_{y,nom}$ as defined by eq (8). In addition to $F_{y,nom}$ also the torque $M_{e,nom}$ corresponding to rated electrical power and the weight of the rotor m.g are used in defining the rotor loads. Table 1 summarizes the design load components.

Table 1. Rotor design loads

Load components	Static load	Dynamic load amplitude
F_x	0	0
M_x	$e \cdot F_{y,nom}$	$0.25 \cdot e \cdot F_{y,nom}$
F_y	$F_{y,nom}$	$0.25 \cdot F_{y,nom}$
M_y	$1.3 \cdot M_{e,nom}$	$0.25 \cdot 1.3 \cdot M_{e,nom}$
F_z	$- m \cdot g$	0
M_z	$e \cdot F_{y,nom}$	$0.25 \cdot e \cdot F_{y,nom}$

The moments are calculated as the result of $F_{y,nom}$ being applied a distance e from the rotor axis, where

$$e = \frac{1}{6} R \tag{22}$$

where R is the radius of the rotor. When calculating the loads on machinery and tower the static loads are as given in table 1 while the dynamic load amplitudes of table 1 are reduced by 33%.

In addition to the aerodynamic forces on the blades, gravity forces are included as dynamic in-plane loading of the blades. Furthermore the main shaft is subject to a torque from the mechanical brake of the magnitude 2 to 2.5 times M_y of table 1.

The loads given here are design loads that should be compared with the design strength of the components according to Danish standards.

3.2. Other requirements

A number of requirements, more or less rules-of-thumb, have been established for the layout of windmills. Many of them are based on engineering judgement and can be applied on inspection of drawings or machinery only. The most important quantifications are:

a. A main shaft of standard steel must have a diameter not less than 1% of the rotor diameter. The quantity of interest is the bending moment of inertia. Based on this rule other shaft layouts or materials may be evaluated.

b. The yaw drive shaft diameter must be not less than 0.33% of that of the rotor. Application of the rule is similar to that of rule a.

c. Stress ranges due to dynamic loads must not exceed 30 N/mm^2 peak-to-peak in welded details.

d. The tower must be analysed by a licensed consulting engineer according to the loads of section 5.2.1.

As mentioned above the load definitions contain load safety factors. Safety factors on material properties should be added.

4. LICENSING REQUIREMENTS

It has already been pointed out that the ad-hoc design basis must be seen together with the functional requirements of the licensing procedure. One reason for getting along with a simple design basis is that by proper functional and conceptual requirements one may avoid operational conditions or configurations that would require much more sophisticated design bases.

An account of the development of the licensing procedure is given by Lundsager (1982) and Jensen (1985). A more detailed description is outside the scope of this paper but the most important features are given below.

4.1 Design requirements

The most important requirements are:

a. There must be two independent brake systems, one mechanical and one aerodynamical. The former must be able to stop the machine under full load.

b. There must be a safety system that detects abnormal conditions. The layout of the safety system aims at preventing overload.

c. The blades must be proof load tested under supervision of the Test Station.

4.2. Licensing procedure

The most important points in the licensing procedure are:

a. The manufacturer must apply for and obtain a license if his machine is to obtain government subsidy.

b. The manufacturer must submit complete drawings and design calculations including wind atlas assessments of annual power production (Petersen et al., 1981) to the Test Stations. This information is treated confidentially of course.

c. The Test Station inspects the machine at the manufacturer's workshop at the prototype stage. This inspection may be combined with one or several visits of a team of consultants from the Test Station.

d. The Test Station inspects the prototype in operation.

e. The Test Station may request that a machine of the type in question be made available by the manufacturer for measurements. This may be done in two ways:

   - Power measurements made by a consultant under contract with the Test station.

   - Standard measurements made at the Test Station (Pedersen, 1983).

   Also specific components may be required for testing at the Test Station.

At any point in the procedure the Test station may require changes in the design. An important part of the licensing is based on engineering judgement that is reached by discussing the specific questions that arise, especially with respect to design.

5. FUTURE DEVELOPMENTS

It is considered of vital importance to extend the presently used ad-hoc design basis into a well-defined windmill design basis. It is no small task for a number of reasons, one of them being that a rigorous theoretical understanding of all phenomena related to windmill design still does not exist.

Therefore, the establishment of windmill standards must be accompanined by a dedicated research and development effort. An example of this is the ongoing work on the development of a rigorous design load standard. The working group on design load standard is chaired by members of the Test Station while project responsibility is held by the Section of Wind Technology, both part of the Department of of Meteorology and Wind Energy at Risø. The work is carried out in cooperation with the Union of Danish Engineers who are responsible for the working out of Danish Standards.

The work is carried out while using results from the program for fatigue life and extreme load prediction reported by Madsen and Frandsen, 1984. A draft standard is expected at the end of this year.

This will be the first step towards an actual complete windmill standard. In this context contact is kept to international and national standards work in other countries, partly within the framework of IEA (Beurskens et al., 1985) and partly by means of the international cooperation among test stations (Petersen, 1984).

However, in the foreseeable future Risø's ad-hoc design basis will be extended and used in parallel with the development of standards, hopefully to merge into the standards as they become operational.

6. CONCLUSION

The Test Station's ad-hoc design basis looks and is simple. It has worked very well so far when applied in connection with the other licensing requirements. Danish windmills have a worldwide reputation for being reliable and rugged machines, however, they are heavier than average. This reflects precisely the aims of the ad-hoc design basis.

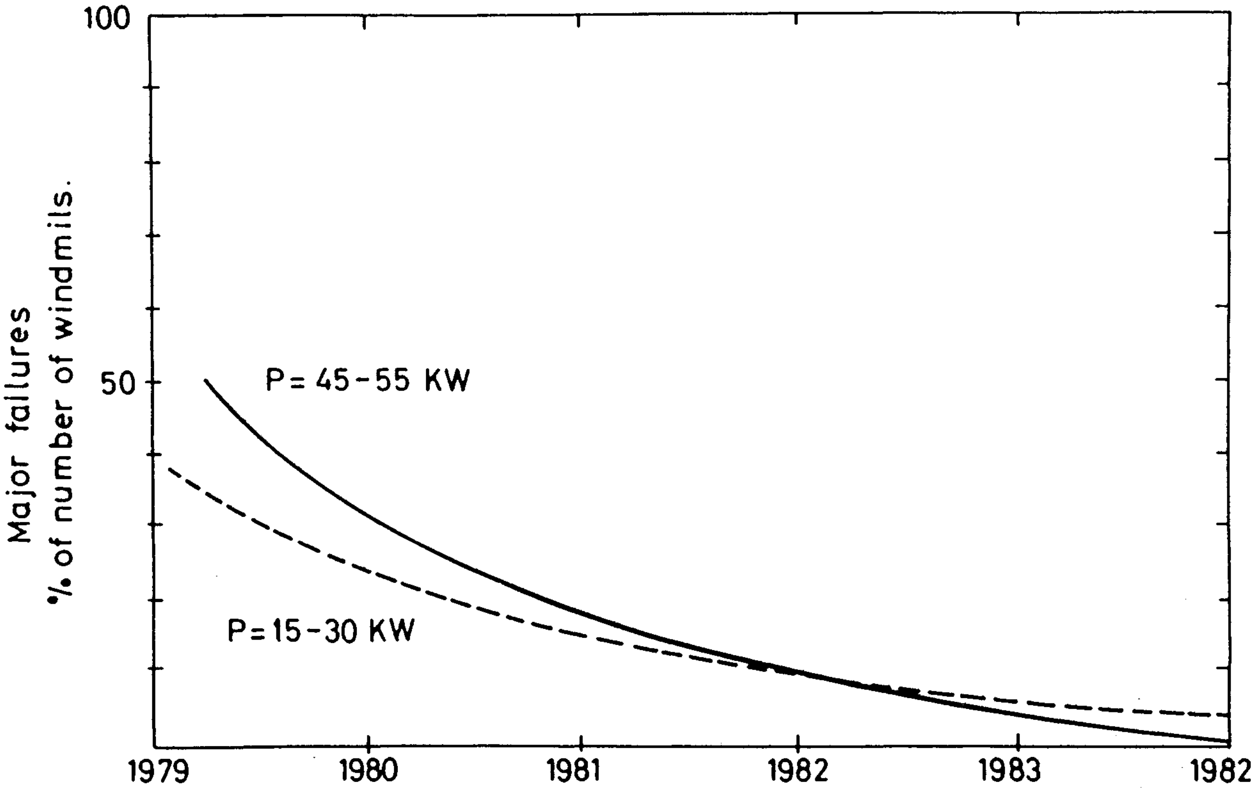

Fig.5. Development of the failure rate for 55-kW windmills in Denmark (Jensen, 1984).

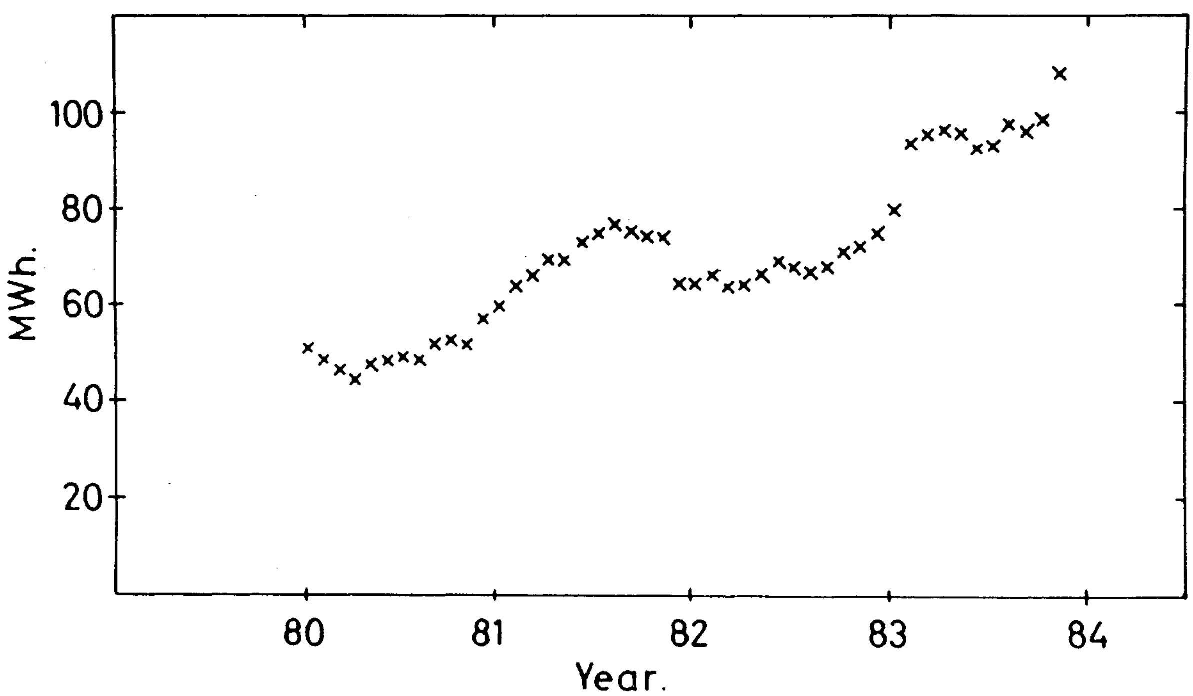

Fig. 6. Development of the average annual power production by 55-kW windmills in Denmark (Jensen, 1984).

Some of the facts behind their reputation are shown in figs. 5 and 6. Here it is shown how the failure rate for the 55-kW machines have fallen to a very low level while the annual average production has doubled at the same time.

The ongoing work on standards development is coupled with coordinated research and development. Hopefully, this will lead to the development of a new generation of Danish windmills that are still rugged and reliable, not too heavy and more efficient.

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REFERENCES

BEURSKENS, J., FRANDSEN, S, LUNDSAGER, P. and PEDERSEN, B.M. (1985). "Review of Standards/Codes of practice Related to Safety and Reliability of WECS". Paper proposed for presentation at the WINDPOWER' 85 Conference, San Francisco, USA, August.

JENSEN, P.H. (1984). "A Survey of Small Danish Windmills", Proceedings of ASME Wind Energy Symposium, Energy Source Technology Conference & Exhibition, New Orleans, USA, February.

JENSEN, P.H. (1985). "Lastparadigma for Vindmøller" (Load cases for Windmills) (In Danish). Note 22.02.1985 PHJ/aj, The Test Station for Windmills, February, 7 pp.

JUUL, J. (1961). "Design of Wind Power Plants in Denmark". Proceedings of the Conference New Sources of Energy, Rome, August 21-31, 229-240.

LADING, P. (1984). "Rules for System Approval of Windmills. Note from The Test Station for Windmills, August, 12 pp.

LUNDSAGER, P. (1982). "Experience With the Gedser Windmill and Small Danish Windmills, March 1982". Proceedings of ASME Wind Energy Symposium, Energy Sources Technology Conference & Exhibition, New Orleans, USA, March, 276-284.

LUNDSAGER, P. PETERSEN, H. and FRANDSEN, S. (1981). "The Dynamic Behaviour of the Stall Regulated Nibe A Wind Turbine. Measurements and a Model for Stall-Induced Vibrations". Risø-M-2253, 70 pp.

LUNDSAGER, P. and JENSEN, P.H. (1982). "Licensing of Windmills in Denmark", Proceedings of Fourth International Symposium on Wind Energy Systems, Stockholm, Sweeden, September, 403-410.

MADSEN, P.H. and FRANDSEN, S. (1984). Wind-Induced Failure of Wind Turbines, Eng. Struct., 6, 281-287.

PEDERSEN, T.F. (1981). "Proof Load Testing of Rotor Blades With Triangular Load Distribution" (In Danish). Risø-M-2281, 9 pp.

PEDERSEN, T.F. (1983). "Standard Measurements on Windmills at the Test Station for Windmills at Risø, Denmark", Proceedings of ASME Wind Energy Symposium, Energy Sources Technology Conference & Exhibition, Houston, Texas, USA, February, 593-606.

PETERSEN, E.L., TROEN, I., FRANSEN, S. and HEDEGAARD, K. (1981). "Wind Atlas for Denmark", Risø-R-428.

PETERSEN, H. (1984). "A Survey of Measuring Methods at Test Stations for Wind Turbines". Final report on a study project performed on request from the Commission of the European Communities, Directorate-General for Energy, Brussels, Contract No. XVII/BR/83/279.3. Risø-M-2452, 72 pp.

RASMUSSEN, F. and PEDERSEN, T.F. (1982). "Measurements and Calculations of Forces on the Blades of a Stall-Regulated HAWT". Proceedings of Fourth International Symposium on Wind Energy Systems, Stockholm, Sweden, September, 59-70.

RASMUSSEN, F. (1983). "Blade and Rotor Loads for Vestas 15", Risø-M-2402, June, 48 pp.

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